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Quest for precision in hadronic physics at low energies: Monte Carlo tools vs. experimental data*

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1 Introduction

The systematic comparison of the Standard Model (SM) predictions with very precise experimental data served in the last few decades as an invaluable tool to test the theory at the quantum level. It has also provided stringent constraints on many "new physics" scenarios. The (so far) remarkable agreement between the precise measurements of the electroweak observables and their SM predictions is a striking experimental confirmation of the theory, even if there are a few observables where the agreement is not so satisfactory. On the other hand, the Higgs boson has not yet been observed, and there are strong theoretical arguments hinting at the presence of physics beyond the SM. Future colliders, like the upcoming LHC or an e^+e^- International Linear Collider (ILC), will hopefully answer many such questions, offering at the same time great physics potential and a new challenge to provide even more precise theoretical predictions.

Precision tests of the Standard Model requires appropriate inclusion of higher order effects and the knowledge of very precise input parameters. One of the basic input parameters is the fine-structure constant α which depends logarithmically on the energy scale. It can be determined at zero momentum transfer with an impressive accuracy of 0.37 parts per billion (ppb) [1] from the measurement of the anomalous electron magnetic moment [1], relying on the validity of the perturbative QED. At Z-mass scale the shift of the fine-structure constant involves low energy non-perturbative hadronic effects, which causes a dramatic reduction of accuracy, by several orders of magnitude [2–5]. These low energy strong-interaction effects can be computed from hadronic e^+e^- annihilation data via the dispersion relation [6]:

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = -\left(\frac{\alpha M_Z^2}{3\pi}\right) {\rm Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\epsilon)}, \tag{1}$$

where $R(s) = \sigma^{(0)}(s)/(4\pi\alpha^2/3s)$ and $\sigma^{(0)}(s)$ is the total cross section for e^+e^- annihilation into any hadronic state.

The current accuracy of this dispersive integral is of the order of 1%, dominated by the error on the hadronic cross section measurement in the energy region below few GeV [7–10, 2–5, 11–14]. This error represents the largest source to the uncertainty of the effective electromagnetic coupling constant, (recent evaluations gives $\Delta\alpha(M_Z^2) = 22 \times 10^{-5}$ [5, 14]), becoming a limiting factor on the effective electroweak mixing parameter $\sin^2\theta_f$, and in turn on the prediction of the Higgs mass [15]. Table 1 (from Ref. [2]) shows that an uncertainty $\delta\Delta\alpha^{(5)}_{\rm had} \sim 5\times10^{-5}$, needed for precision physics at a future linear collider, requires the measurement of the hadronic cross section with a precision of $O(1\%)$ from threshold up to the Υ peak.

$\delta\Delta\alpha^{(5)}_{\rm had}\times10^5$	$\delta(\sin^2\theta^{\rm lept}_{\rm eff})\times10^5$	Request on R
22	7.9	Present
7	2.5	$\delta R/R \sim 1\%$ up to J/ψ
5	1.8	$\delta R/R \sim 1\%$ up to Υ

Table 1. [2] Values of the uncertainties $\delta\Delta\alpha^{(5)}_{\rm had}$ (first column) and the errors induced by these uncertainties on the theoretical SM prediction for $\sin^2\theta^{\rm lept}_{\rm eff}$ (second column). The third column indicates the corresponding requirements on the R measurement.

Like the effective fine-structure constant at the scale M_Z, the SM determination of the anomalous magnetic mo-

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ment of the muon a_μ is presently limited by the evaluation of the hadronic vacuum polarisation effects, which cannot be computed perturbatively. However, using analyticity and unitarity, it was shown long ago that this term can be computed from hadronic e^+e^- annihilation data via the dispersion integral [16]

$$a_\mu^{\rm HLO} = (1/4\pi^3)\int_{4m_\pi^2}^{\infty} ds\, K(s)\sigma^{(0)}(s) = (\alpha^2/3\pi^2)\int_{4m_\pi^2}^{\infty} ds\, K(s)R(s)/s\,. \quad (2)$$

The kernel function $K(s)$ decreases monotonically for increasing s. This integral is similar to the one entering the evaluation of the hadronic contribution $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$ in Eq. (1). Here, however, the weight function in the integrand gives a stronger weight to low-energy data. A recent compilations of e^+e^- data gives [17]:

$$a_\mu^{had} = (695.5 \pm 4.1) \times 10^{-10}\,. \quad (3)$$

Similar values are obtained by other groups [14,18–20].

By adding this contribution to the rest of the SM contributions, a recent update of the SM prediction of a_μ, which uses the result in [21] gives [17,22]: $a_\mu^{\rm SM} = 116591834(49)\times 10^{-11}$. The difference with the experimental average [23], $a_\mu^{\rm exp} = 116592080(63)\times 10^{-11}$. is then $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = +246(80)\times 10^{-11}$, i.e., 3.1 standard deviations (all errors were added in quadrature). Slightly higher discrepancies are obtained in Refs. [14,19, 20] . As in the case of $\alpha(M_Z^2)$, the uncertainty on the theoretical evaluation of a_μ is still dominated by the hadronic contribution, and a reduction of the uncertainty is necessary in order to match the precision of the proposals experiments on the measurement of a_μ at FNAL [24] and J-PARK [25].

Precise determination of the hadronic cross sections (accuracy $\le 1\%$) requires a deep control of high order effects like Radiative Corrections (RC) and non-perturbative hadronic contribution to the running of α (vacuum polarisation, VP) into Monte Carlo (MC) programs. Particularly in the last years, the increasing precision reached on the experimental side at the e^+e^- colliders (VEPP-2M, DAϕNE, BEPC, PEP-II and KEKB) led to the development of dedicated high precision theoretical tools: Babayaga (and its successor Babayaga@NLO) for the measurement of the luminosity, MCGPJ for the simulation of the exclusive QED channels, and PHOKHARA for the simulation of the process $e^+e^- \to hadrons + \gamma$, are examples of MC generators which include NLO corrections with per mill accuray. In parallel to these new efforts, well-tested codes such as BHWIDE (developed for LEP/SLC colliders) were adopted.

Theoretical accuracies of these generator were estimated, whenever possible, by evaluating high order missing contributions (from this point of view, the great progress in the calculation of two-loop corrections to the Bhabha scattering cross section was essential to establish the theoretical accuracy of the existing generators for the luminosity measurement). Usually only analytical or semi-analytical estimates of missing terms exist which don't take into account realistic experimental cuts. In addition MC event generators include different parametrisation for the VP, which affect the prediction (and the precision) of the cross sections, and RC are usually implemented with different formulations.

From the above arguments it becomes evident how important are the comparisons of MC generators for a common set of input parameters and experimental cuts. Such a *tuned* comparisons, which started in the LEP era, are a key step in the validation of the generators, since it allows to check that the different details entering the complex structure of the generators themselves are under control, and free by possible bugs. This was the main motivation for the "Working Group on Radiative Corrections and Monte Carlo tools", (RADIO MONTECARLO), which was formed 3 years ago bringing together experts (theorists and experimentalists) working on the field of low energy e^+e^- physics and partly also the τ community.

In addition to tuned comparisons, the technical details of the MC generators, the recent progress (like new calculations), and the open issues were also discussed in regular meetings.

This report is a summary of all these efforts: it provides a self-contained and up-to-date description of the progress occurred in the last years towards precision hadronic physics at low energy, together with new original results like comparisons and estimates of high order effects (like pion pair correction to the Bhabha process) in presence of realistic experimental cuts.

The report is divided in five sections: the first three are devoted to the status of the MC tools for Luminosity R-scan, and Initial State Radiation (ISR), respectively.

Tau spectral function in hadronic decays are also used to estimate $a_\mu^{\rm had}$, since they can be related to to e^+e^- annihilation cross section via isospin symmetry [26–29]. The substantial difference between the e^+e^-- and τ-based determinations of $a_\mu^{\rm had}$, even if isospin violation corrections are taken into account, shows that further common theoretical and experimental efforts are necessary to understand this phenomenon. Section four discusses the experimental status and MC tools for tau decays. The recent improvements in generators TAUOLA and PHOTOS are discussed there and prospectives for further developments are sketched.

The section five focuses on the theoretical treatment of non-perturbative effects of light quarks to the Vacuum Polarisation, which is a key ingredient in the high precision measurement of the hadronic cross section.

2 Luminosity

luminosity [30]

3 Scan

scan

4 Radiative return

radiative return

5 Vacuum polarization

vacuum polarization

6 Tau physics

tau physics

7 Summary

summary

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